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TRIGGERED LIGHTNING AND SOME UNSUSPECTED LIGHTNING HAZARDS

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13. ABSTRACT

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It is pointed out ~~that~~ solid-state devices and microcircuitry, computers, plastics, and electrically composite materials, are all quite vulnerable to the effects of lightning. These components are being increasingly used in aircraft construction and operation. Also, as aircraft become bigger and faster they have a greater propensity to trigger lightning. Therefore it is concluded that the lightning hazard to aircraft operation is increasing.

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NOTE

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STANFORD RESEARCH INSTITUTE
Menlo Park California 94025 U S A

AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE
138th ANNUAL MEETING, PHILADELPHIA, 1971

TRIGGERED LIGHTNING AND SOME UNSUSPECTED LIGHTNING HAZARDS

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BRIEF SUMMARY

This paper considers instances of lightning initiated by man's activities. These include the triggering of lightning by high-rise buildings and other tall structures; by rockets trailing wires; by the column of water thrown up by a depth-charge; by the large Apollo 12 rocket; by aircraft; and by thermonuclear explosions. All the incidents occur when the ambient electric field is some 10,000 volts per meter, and the voltage discontinuity between the conductor initiating the lightning and the adjacent atmosphere is about a million volts.

It is pointed out that solid-state devices and micro-circuitry, computers, plastics, and electrically composite materials, are all quite vulnerable to the effects of lightning. These components are being increasingly used in aircraft construction and operation. Also, as aircraft become bigger and faster they have a greater propensity to trigger lightning. Therefore it is concluded that the lightning hazard to aircraft operation is increasing.

I INTRODUCTION

We define triggered lightning as lightning that is caused by some human modification of the natural atmospheric environment. This definition excludes lightning that has been occasionally reported as occurring in dust-storms, in snow-blizzards, within the clouds above active volcanoes, and in association with earthquakes. All these lightning occurrences--although unusual--are in accompaniment to a natural phenomenon; the lightning is not due to any man-made activity.

Almost all instances of lightning triggered by man, either by design or by accident, involve the introduction of a long electrical conductor into a thundery environment where the general electric field is some 10 kilovolts per meter (kV/m). If the potential discontinuity between the tip of the conductor and the ambient atmosphere becomes about a million volts (10^6 V) a leader-streamer is initiated from the conductor and triggered lightning can occur. We may differentiate between two main categories of triggered lightning:

(a) The conductor is connected to earth. Examples are shown in Figure 1. These include lightning triggered by a tall building, and discharges initiated by the sudden introduction of a conductor (depth-charge column of water; rocket carrying a wire) into a thundery environment.

(b) Conductor is in free flight. Examples are shown in Figure 2. They include discharges triggered by rockets (Apollo 12) and by aircraft.

Equipotential surfaces are indicated on Figures 1 and 2; however, the motion of, and the charges carried by, rockets and aircraft, may cause appreciable distortions from the representation of Figure 2. The greatest electric fields are where the equipotentials are closest spaced that is at the extremities of the conductors. It is at these points that the leader-streamers initiating lightning develop.

It is most appropriate in this city (Philadelphia) and at this meeting to mention that Franklin's classic kite experiment could well have resulted in an instance of triggered

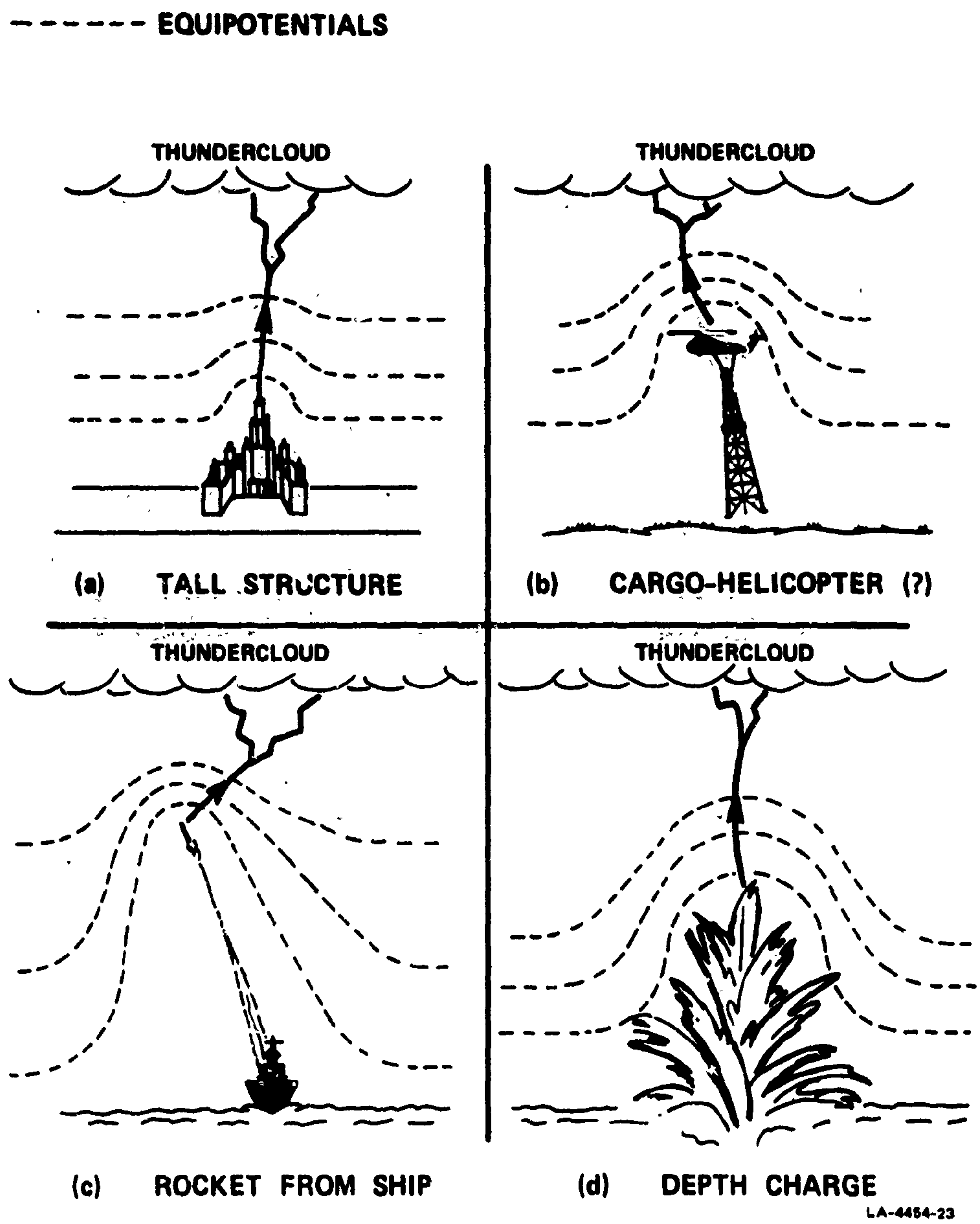


FIGURE 1 EXAMPLES (diagrammatic) OF TRIGGERED LIGHTNING

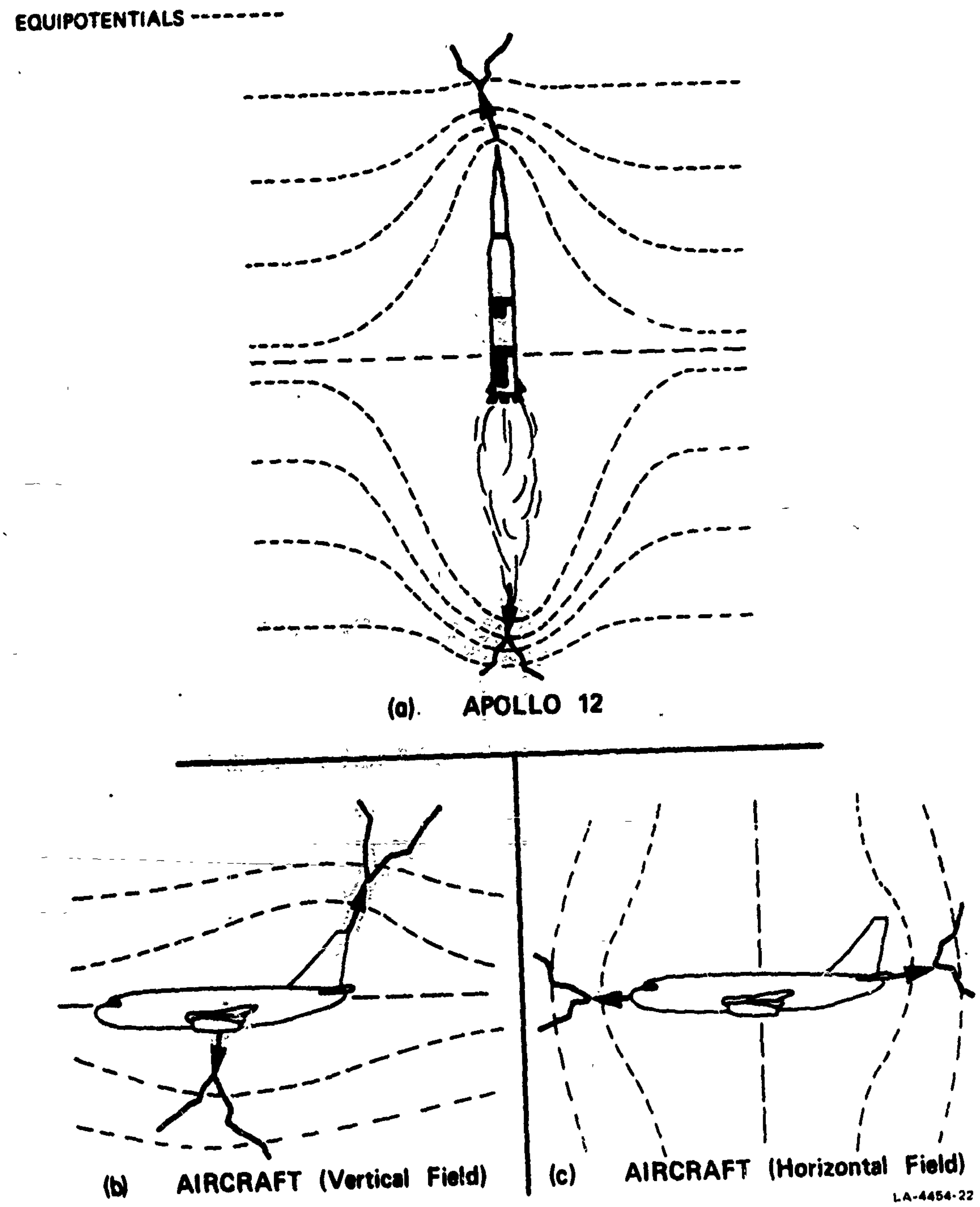


FIGURE 2 FURTHER EXAMPLES (diagrammatic) OF TRIGGERED LIGHTNING

lightning similar to some of those on Figure 1. Fortuitously, but most fortunately for humanity in general and the U.S.A. in particular, Franklin's kite did not trigger lightning. Other kites flown later under circumstances similar to those of Franklin's experiment have, as indeed is occasionally to be expected, triggered lightning, with the result that the kite flyers have sometimes been killed.[1]

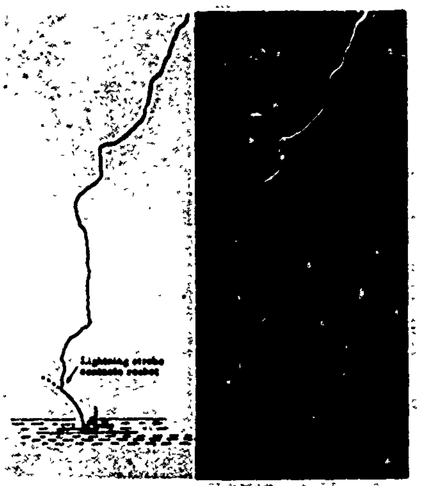
II LIGHTNING TRIGGERED BY TALL STRUCTURES

Conventional cloud to ground lightning is initiated by a leader that travels from the cloud towards the earth. However, the classic work of McEachron[2] on the Empire State Building showed that lightning to the building is usually started by a leader moving upwards from the tip of the building towards the charged cloud. In other words, lightning is triggered by the presence of the building. Figure 3(a) shows an example of lightning initiated by the Moscow State University tower.

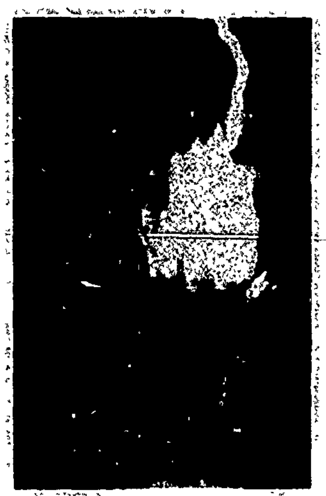
Figure 4 summarizes some data on the incidence of lightning flashes to tall structures (buildings, TV towers, etc.). The data are for temperate latitudes and have been drawn from several sources.[2,3,4,5,6,7,8] An adjustment to an isoceraunic (thunderstorm days per annum) level of 32 has been made. We note that structures less than about 150 meters (m) in height are only struck by conventional lightning. However, with increasing height there is a very rapid increase in the proportion of flashes initiated by the structure; for a structure height of 200 m it is about 50 percent, and at 400 m it exceeds 80 percent.

The conditions for the development of a leader-streamer from the tip of a conductor depend upon the electric field magnitude and configuration in the vicinity of the tip. The breakdown field must be exceeded over some distance from the tip and not only at the tip itself; otherwise, even such a minor breakdown as point corona would produce leader-streamers. In the case of a tall structure, the field configuration at its top is controlled by the general ambient field, E_a, the height, H, of the structure, and its shape; this last, is a factor for which a normalizing adjustment between different structures is impracticable. However, we may define two parameters which can readily be estimated, and which are quantitatively indicative of the thresholds for the development of leader-streamers and therefore

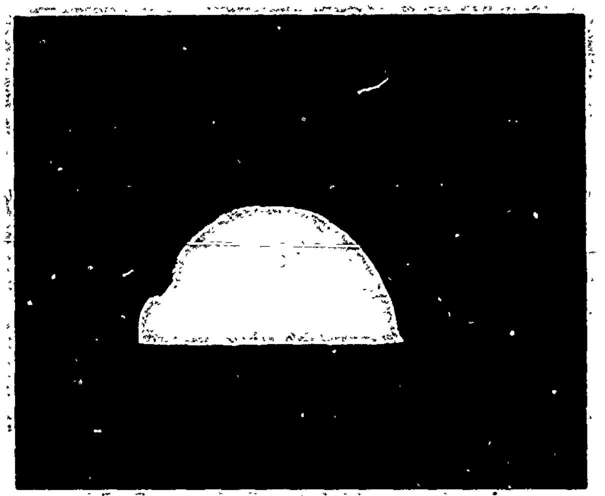
(a) TALL BUILDING



(b) ROCKET



(c) DEPTH CHARGE



(d) NUCLEAR

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FIGURE 3 INSTANCES OF TRIGGERED LIGHTNING

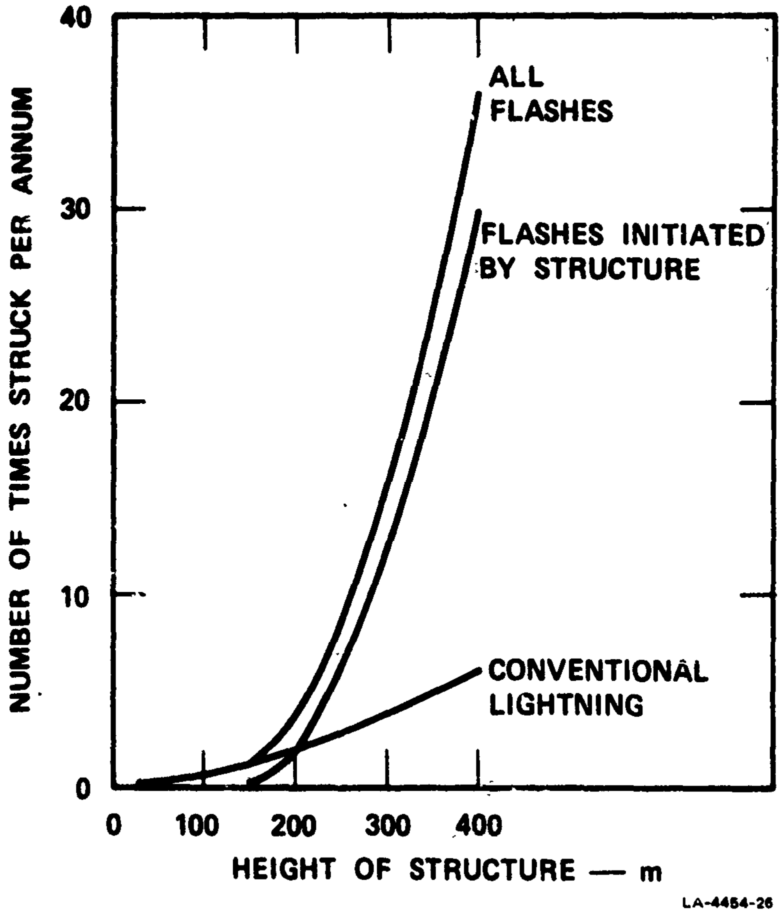

FIGURE 4 DATA ON FLASHES TO TALL STRUCTURES
(Isoceraunic Level — 32)

for the triggering of lightning. These parameters are:

(a) The general ambient field E_a. Since the field near the surface of the earth is vertically directed we may equate E_a and E_h where h is the height coordinate.

(b) A parameter which we may call the voltage discontinuity V_d. For a tall structure we may equate $V_d = V_H = \int_o^H E_h dh$. Essentially, V_H approximates the voltage difference between the tip of the structure and the ambient atmosphere.

Broadly speaking, the value of V_d has to be greater than a certain threshold before a leader-streamer can be initiated; whether the streamer subsequently becomes self-propagating depends on a critical value of E_a being exceeded. Thus both V_d and E_a are involved in determining the criterion for the occurrence of triggered lightning.

One point should be mentioned. The subscript h indicates that the ambient field $E_a = E_h$ is a function of height. When there is a thundercloud overhead the strong electric fields at ground level cause points such as trees at the surface of the earth to go into corona. The resulting ionic space charge is distributed between the ground and the thundercloud, and it follows from Poisson's equation that because of the space charge the field E_h should increase with increasing height. The magnitude of the increase is uncertain. It may be by tenfold or more; it may be slight. The experimental evidence is confused. However, it is generally agreed that E_h certainly does <u>not decrease</u> between ground (field $= E_o$) and cloud levels. Also, because of the effective absence of surface points and irregularities over sea E_o is probably substantially greater than over land, while the increase of E_h with height is less pronounced.

Figure 5 presents some data, derived from Simpson's measurements,[9] regarding the magnitudes of the surface field (E_o) during a typical land thunderstorm. Obviously the field rarely exceeds 10 kV/m. We may associate this effective maximum experienced value for E_o with the minimum height--150 m--needed to trigger a lightning discharge (Figure 4). It follows that $V_H \gtrsim 150 \times 10$ kV $\gtrsim 1.5 \times 10^6$ V where the $\gtrsim$ sign makes allowance for the possible increase of E_h with height.

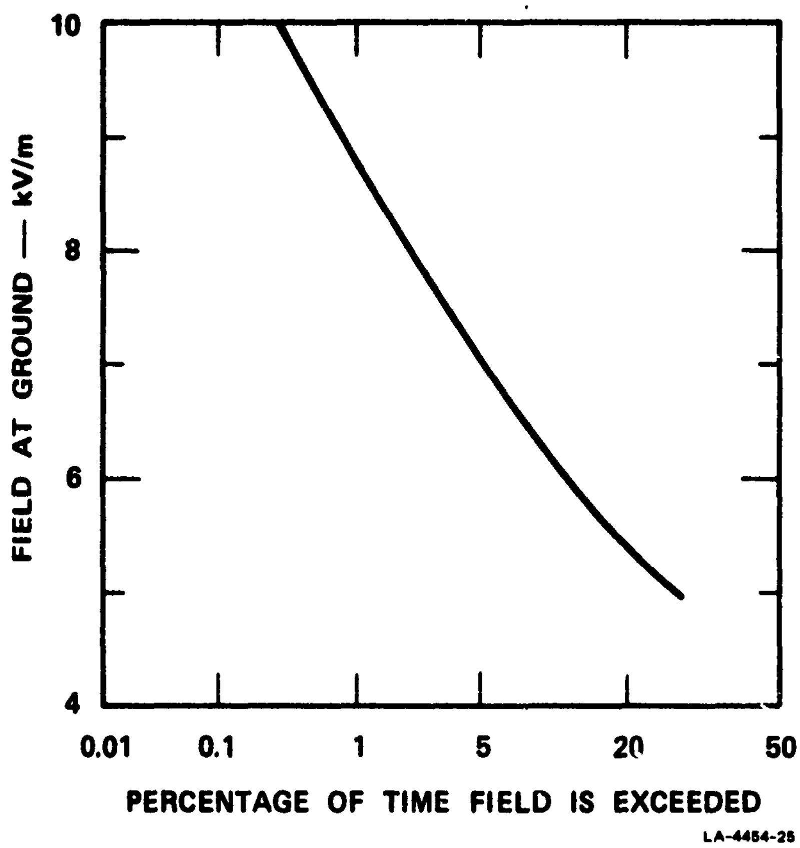

FIGURE 5 STATISTICAL DATA ON SURFACE FIELDS IN A THUNDERSTORM ENVIRONMENT

Estimates of V_H can also be made for certain specific structures. Bruce[10] deduced that discharges could be initiated by the Empire State Building when the average field between the ground and the tip of the building was only 5 kV/m. Since the height of the Building is 380 m this gives $V_H = 1.9 \times 10^6$ V. Müller-Hillebrand[11] has discussed an instance of upward leaders occurring simultaneously from two towers, each 70 m tall, situated near the 600 m high summit of Monte San Salvatore. At the time the ground field E_o was approximately 3 kV/m. Evidence[6] suggests that the "effective" height of the towers is increased by perhaps 200 m as a result of their location near the summit of a sharply peaked mountain. It follows that $V_H \geq 8.1 \times 10^5$ V.

Solak[12] has pointed out [Figure 1(b)] that a cargo-helicopter when its load is near the ground acts effectively as a tall structure, and as such is vulnerable to a triggered lightning hazard when in a thundery environment. The hazard may be increased by the charge carried on the helicopter producing a local breakdown, and therefore a sudden conducting connection, between the load and the ground. Tethered balloons[13] are another type of tall structure that can initiate triggered lightning.

III LIGHTNING TRIGGERED BY ROCKETS TRAILING WIRES

There have been many attempts to trigger lightning by firing rockets trailing conducting wires into thunderclouds. These efforts have met with little success over land. Over sea, however, Newman and his associates[14] have triggered lightning on several occasions; Figure 3(b) shows an example. The better success for sea as compared with land is to be expected, since because of the lesser point-discharge (and consequent space-charge) effects, the surface fields--and therefore the effective electrical perturbation due to the rocket--are greater over a sea-surface than over solid terrain.

Triggering over the oceans has occurred with the rocket at heights of between 100 and 300 m. The fields were about 18 kV/m both at the sea-surface and at the cloud base.[15] It follows that V_H is 1.8 to 5.4 megavolts.

IV THE DEPTH-CHARGE INCIDENT

This famous instance [Figure 3(c)] of triggered lightning occurred when depth-charges were being tested in Chesapeake Bay during thundery weather.[16] Much to the surprise of all concerned, when the plume of water thrown up by one charge had reached a height of about 70 m a lightning flash occurred to the top of the plume. The discharge was of long duration and persisted as the water-plume continued to rise. The flash included at least three component strokes.

No measurements of electric field were being made at the time of the depth-charge incident. However, measurements made under similar circumstances[15] suggest surface fields of perhaps 10 to 20 kilovolts per meter. Hence V_H is 0.7 to 1.4 megavolts.

V THE APOLLO 12 INCIDENT

The lightning strikes to the Apollo 12 space vehicle shortly after its launch on November 14, 1969, have been thoroughly investigated.[17] It is generally agreed that the discharges were triggered by the presence of the vehicle. The flashes occurred when the vehicle was within cloud and at altitudes of approximately 2,000 m and 4,400 m. No lightning was reported in the immediate vicinity of the launch-pad before the launch, although a few isolated flashes probably occurred within 30 km of the launch area during the 30 minutes prior to launch.[15] However, although the clouds above the launch-pad were not active thunderclouds they were undoubtedly strongly electrified, and a reasonable estimate[15,17] for the surface field is 3 to 4 kV/m.

Figure 2(a) is a diagrammatic representation of electrical conditions around the Apollo 12 vehicle in free flight The representation is probably unrealistic for several reasons. It shows the exhaust as extending the electrically conducting length of the vehicle system by an amount approximately equivalent to the length of the rocket; the effective conducting extension by the exhaust could well be either much greater or much less than this. Figure 2(a) assumes that the vehicle-exhaust system has attained electrical equilibrium with its surroundings so that the potential of the ambient atmosphere and of the system at its midpoint are equal; because of the rocket motion it is unlikely that this

equilibrium situation will ever be approached Charges on the vehicle will distort the electrical representation of Figure 2(a). Experiments with instrumented rockets show that because of engine charging currents rockets can acquire a substantial charge following lift-off as soon as the conducting connection with the ground is broken. Furthermore, vehicle impact with precipitation elements can develop very large charges on the vehicles.[18]

There are obviously considerable uncertainties in estimating values of ambient electric field and voltage discontinuity for the Apollo incident. Most workers in atmospheric electricity believe that with a ground level field of 3 kV/m the field within the cloud above would be at least 10 kV/m; we will adopt this figure as a minimum value for the ambient field E_a. For the case of an airborne pointed conductor in electrical equilibrium with its atmospheric environment the voltage discontinuity, V_d, at the ends of the conductor is approximately $E_a(\ell/2)$ where ℓ is the "electrical" length of the conductor. We assume that electrical equilibrium is attained, but there are still difficulties for Apollo 12 in estimating ℓ, since we must add a rather uncertain amount to the actual length--110 m--of the vehicle in order to allow for a conducting exhaust trail. Calculations[19] suggest that at an altitude of about 2,000 m, 300 m is not an unreasonable estimate for the conducting length of the exhaust trail. Ground-level observations show that during the launch of Apollo vehicles the exhaust maintains a conducting connection with ground over a length exceeding 100 m, while actual in-flight measurements made with other large rockets indicate that this connection is abruptly broken at a trail length of about 200 m. Since exhaust conductivity increases with altitude these ground level values are quite compatible with a trail estimate of 300 m at 2,000 m. We will therefore consider ℓ to be 400 m, (300 + 100), for the Apollo 12 incident; hence with E_a = 10 kV/m we have $V_d = 2 \times 10^6$ V.

VI LIGHTNING TRIGGERED BY AIRCRAFT

Although aircraft are often struck by lightning it is usually impossible to determine whether the flash was initiated by the presence of the aircraft or not. However, there are at least two[20,21] published accounts of several instances in which the lightning was almost certainly triggered by aircraft. In most of these cases the flashes occurred while

aircraft were penetrating dissipating thunderstorms which had ceased to produce lightning; the only discharges that took place during these penetrations were to the aircraft. It is also understood[22] that during the development of the Boeing 747 test flights were made in which the aircraft was flown in and out of clouds that were strongly electrified but not actually generating lightning. The 747 was consistently struck soon after entering the clouds; no other lightning, except that to the 747, occurred.

If we accept that a certain voltage discontinuity is necessary in order to initiate a leader-streamer it follows that the bigger an aircraft (greater ℓ) the more likely it is to trigger lightning. There are indeed indications that, under comparable environmental conditions, the large aircraft now coming into widespread service are struck more frequently than their smaller predecessors. However, the available statistics are limited in extent and need careful interpretation. There is also some evidence that high-speed aircraft experience more lightning strikes than their slower fore-runners. It is tempting to associate this behavior with an effective electrical extension--as in the case of a rocket--of the aircraft by a conducting exhaust plume, but even for a high-performance fighter aircraft the exhaust plume is only a few meters in length.[23] However, it should be recognized that an aircraft in flight is trailed by a cloud of ions, generated within the engine exhaust and also by corona from the aircraft. This ionic trail although not of itself a good conductor is nevertheless much more conducting than the undisturbed atmosphere. It seems quite plausible that a lightning leader encountering such a trail could be "led" towards the aircraft, especially if--as is believed--photoelectric processes occur in front of the leader tip.[17] Since an ionic exhaust trail will preserve its identity to longer distances behind the faster aircraft, the chance of strokes being diverted along the trail should increase with increasing aircraft speed.

Electric fields within thunderclouds are predominantly vertical in orientation but there can be substantial horizontal components as well. Figures 2(b) and 2(c) show diagrammatically the electrical conditions possibly leading to the initiation of leader-streamers from aircraft for the two idealized cases of entirely vertical and entirely

horizontal fields. As in the case of Figure 2(a) the assumption--probably unrealistic--of electrical equilibrium with the ambient atmosphere is made, while the effects of charge on the aircraft are ignored.

The instances of triggered lightning to an F-100 aircraft reported by Fitzgerald[20] occurred when the pre-discharge ambient electric field was about 30 kV/m vertically and 6 kV/m horizontally. The maximum dimensions of the F-100 are approximately 5 m vertically and 15 m horizontally. It follows that--assuming equilibrium with the ambient atmosphere--the voltage discontinuities are 75 kV for a vertical flash and 45 kV for one horizontally directed. The strikes described by Cobb and Holitza[21] were to a DC-6 (vertical dimension 9 m; horizontal dimension 36 m) and occurred in ambient fields of some 16 kV/m vertically and 2 kV/m horizontally; the corresponding voltage discontinuities are 72 kV and 36 kV.

VII AN UNUSUAL INCIDENT

Figure 3(d) shows lightning triggered by the detonation of the first thermonuclear device; this event, of 10.4 megatons yield, was set off at Eniwetok in the Marshall Islands on October 31, 1952.[24] Figure 3(d) is an enlargement of one frame of a high speed film. Study[25] of the other frames reveals that the lightning discharges were initiated from surface structures and developed as upward leader-streamers in entirely the same manner as more conventional triggered lightning from tall buildings [Figure 3(a)].

In one respect, however, this example of triggered lightning differs from all the others we have considered. In the previous examples, man provided the perturbation in the electrical environment necessary for the triggered lightning, but the environment was created by natural causes. In the present instance, however, the charge producing the electrical environment is itself generated by the explosion. The charge is developed by gamma rays emanating from the detonation and interacting with the atmosphere to create Compton electrons. Calculations[25] yield a value of 30 kV/m for the field due to the gamma-Compton mechanism. The flashes were apparently initiated from antenna-towers and similar structures carrying instrumentation; 10 m would be a reasonable estimate for their height. Hence, the voltage discontinuity is 3×10^5 V.

VIII SUMMARY AND DISCUSSION OF TRIGGERED LIGHTNING INCIDENTS

Table I summarizes the incidents of triggered lightning that we have considered; the table extends some information previously presented.[26] The deduced values for ambient field and voltage discontinuity are quite consistent. Obviously if the electric field in the atmosphere is about 10 kV/m, and we introduce a conductor into that field so that the voltage difference between the conductor and the adjacent atmosphere approaches 10^6 V, then we may expect triggered lightning. These two quite general criteria can readily be applied to predict the hazard represented by triggered lightning under many different circumstances.

TABLE I

TRIGGERED LIGHTNING INCIDENTS

Type of Incident	Ambient Field (kV/m)	Length of Conductor (m)	Voltage Discontinuity (kV)
<u>Tall Structures</u>			
General Statistics	≥ 10	150	$\geq 1.5 \times 10^3$
Empire State Building	5	380	1.9×10^3
Monte San Salvatore Tower	≥ 3	270*	$\geq 8.1 \times 10^2$
<u>Rocket Trailing Wire</u>	18	100 to 300	1.8 to 5.4×10^3
<u>Depth-Charge</u>	10 to 20 (?)	70	0.7 to 1.4×10^3
<u>Apollo 12</u>	≥ 10	400+	$\geq 2 \times 10^3$
<u>Aircraft</u>			
F-100	6 to 30	15 to 5	45 to 75
DC-6	2 to 16	36 to 9	36 to 72
<u>Thermonuclear</u>	30	10	3×10^2

*Effectively extended by shape of mountain.

+Effectively extended by exhaust trail.

There are only two entries in Table I which show very large deviations from the general pattern. These are the two aircraft incidents, for which the deduced values of the voltage discontinuity are less than 10^5 V; the average for all incidents is of the order of 10^6 V. However, it should be recalled that in the analysis any effects due to charge on

the aircraft have been ignored. It is well known that when flying through clouds aircraft can become charged to such an extent that their potential may be several hundred kilovolts with respect to the neighboring atmosphere.[18] This potential is presumably available to supplement the voltage discontinuity due to the ambient field alone, and thus lead to the initiation of leader-streamers. Certainly the charge carried by aircraft and rockets should be considered when their propensity to trigger lightning is being assessed. We have investigated two reports[20,21] of triggered lightning incidents to aircraft. It is perhaps very significant that in the first instance[20] strong charges were measured on the aircraft, while in the other case[21] the strikes occurred when the aircraft was encountering a mixture of rain and graupel; precipitation-impact charging currents are notoriously high under these conditions.

IX SOME UNSUSPECTED LIGHTNING HAZARDS

Our session this afternoon is to deal with some of the practical dangers associated with lightning. Specifically we are to consider shocks to human beings, lightning effects on forests, and methods of lightning protection. All these topics, although still of much practical relevance, have been subjects of interest for many years. It is therefore appropriate to supplement their discussion by considering some of the more novel aspects in which our way of life is being inconvenienced by lightning. Most of these newer hazards follow directly from technological improvements; such improvements often entail--unfortunately--an increased vulnerability to lightning.

A. Vulnerability of Solid-State Circuitry

The electrical interference caused by lightning may be separated into two main categories. We have the electromagnetic signals radiated into the atmosphere by the discharge, and the surges traveling along power-lines that are either struck or experience near misses. Extraneous noise inductively coupled into electronic circuitry is a familiar interfering factor in many systems. However, modern electronic systems make increasing use of semiconductors and low-signal level microcircuits, and these are much less tolerant of transient voltage and current surges than were the vacuum tubes and large electronic

components of the past.[27,28] Both induced coupling effects and surges introduced through power supplies can readily cause malfunctions and even permanent damage to transistors and solid-state diodes.

B. Vulnerability of Computers

Computer operations are perhaps especially vulnerable to lightning. The effects of power surges can range from the inconvenience of lost time, when the operation in progress has essentially to be reaccomplished, to the extreme of serious damage to magnetic disks, recording arms, and so on. Even more alarming are the possible results of a flash occurring very close to an insufficiently shielded computer. It appears that the magnetic and electromagnetic fields radiated by the flash can seriously modify the core memory cells of a computer. The consequences in such areas as banking, where customers' affairs are increasingly monitored by computer surveillance, could obviously be disastrous.

C. Vulnerability of Modern Materials

Modern technology involves the widespread use of plastics which--normally--are electrical insulators. Also, electrically composite materials, for example those which utilize fibers such as carbon or boron embedded in a plastic matrix, are being increasingly employed. The behavior of both plastics and composites when subjected to lightning currents is much less satisfactory than that of conventional metals, with the chance of material damage being much greater. There are also some subtle features. For example, as metals are replaced by less electrically conductive materials, the inherent safety of shielding by "Faraday-cage" effects is reduced. Furthermore, in electrically inhomogeneous systems the currents are channeled preferentially into the better conducting media; therefore current densities and induced fields are increased and deleterious effects are consequently enhanced.

In some instances, many factors, related to modern developments, contribute to a lightning hazard. For instance, TV towers exceeding 300 m in height are now quite common structures. These towers are convenient high platforms for some equipment; examples are meteorological sensors and radio communication links. Almost inevitably the equipment will

include solid-state circuitry and use plastic materials in its fabrication. Thus we have the structure, because of its height, triggering many flashes to the tower; we have vulnerable solid-state components experiencing this intense lightning exposure; we also have damage-prone plastic materials encountering the same exposure; and we have the secondary effects of diminished "Faraday-cage" protection and increasing channeling of lightning currents.

D. Vulnerability of Aircraft

The relationship between aircraft operation and lightning is presently one of much interest; there are strong indications that the overall lightning hazard is tending to increase. Some of the main areas concerned are listed in Table II; the list is not exhaustive but obviously the sum of present trends in aircraft design and operation acts to augment the lightning hazard. The civil jet aircraft of 1959 was constructed largely of metal; cruised at 35,000 feet and could thus avoid most active thunderstorms; was fitted with rugged electronics; and relied more during operation on pilot judgment than on automatic controls. By all appearances the supersonic aircraft of--say--1979 will be constructed of plastics and composite materials; will cruise at 60,000 feet; will use only solid-state circuitry and components; and will follow a preset flight plan entirely computer controlled. A cursory examination of Table II shows that the lightning hazard will be much greater for the 1979 aircraft than for its predecessor of 1959, unless some of the problems discussed above are solved.

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TABLE II

LIGHTNING AND AIRCRAFT OPERATION

Trend in Aviation	Result	Lightning Hazard
Bigger Aircraft	More Triggered Lightning	Increased
Faster Aircraft	Minor Damage Increased by Wind-Loading	Increased
	More Triggered Lightning (?)	Increased
Better Climb Rate	Less Time at Lower Altitudes	Decreased
More Traffic	More Time in Holding Patterns	Increased
Greater Use of Plastics	More Material Damage by Strike	Increased
	Concentration of Current in Remaining Metal	Increased
Greater Use of Composite Materials	More Material Damage by Strike	Increased
	Concentration of Current in Remaining Metal	Increased
Greater Use of Solid-State Electronics	Greater Vulnerability to Lightning Transients	Increased
More Reliance on Electronic Flight Controls	Greater Vulnerability to Lightning Transients	Increased
More Reliance on Preprogramming of Flight on Airborne Computer	Greater Vulnerability to Lightning Transients	Increased

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